

Integrated Modelling of ASDEX Upgrade nitrogen seeded discharges

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OUTLINE

- Introduction
- Physical Model
- Simulations of AUG plasmas
- Summary

MOTIVATION

- Power exhaust in ITER is not solved problem
- ITER like wall at JET
 - need to develop integrated plasma scenarios
 - Successful experiments at JET with seeded impurities to reduce heat load to target plates:
 - ❖ Type III ELM My H-mode discharges with nitrogen seeding – **high density**
 $\gamma_{rad} = 80\%, n=n_G, H=0.75$ ($I_p=2.5, 3$ MA)
 - ❖ Type I ELM My H-mode discharges with nitrogen seeding
 - ❖ Neon seeded AT discharges ($I_p=1.9$ MA, BT=3.1) – **low density**
 - Similar experiments at AUG with nitrogen seeding

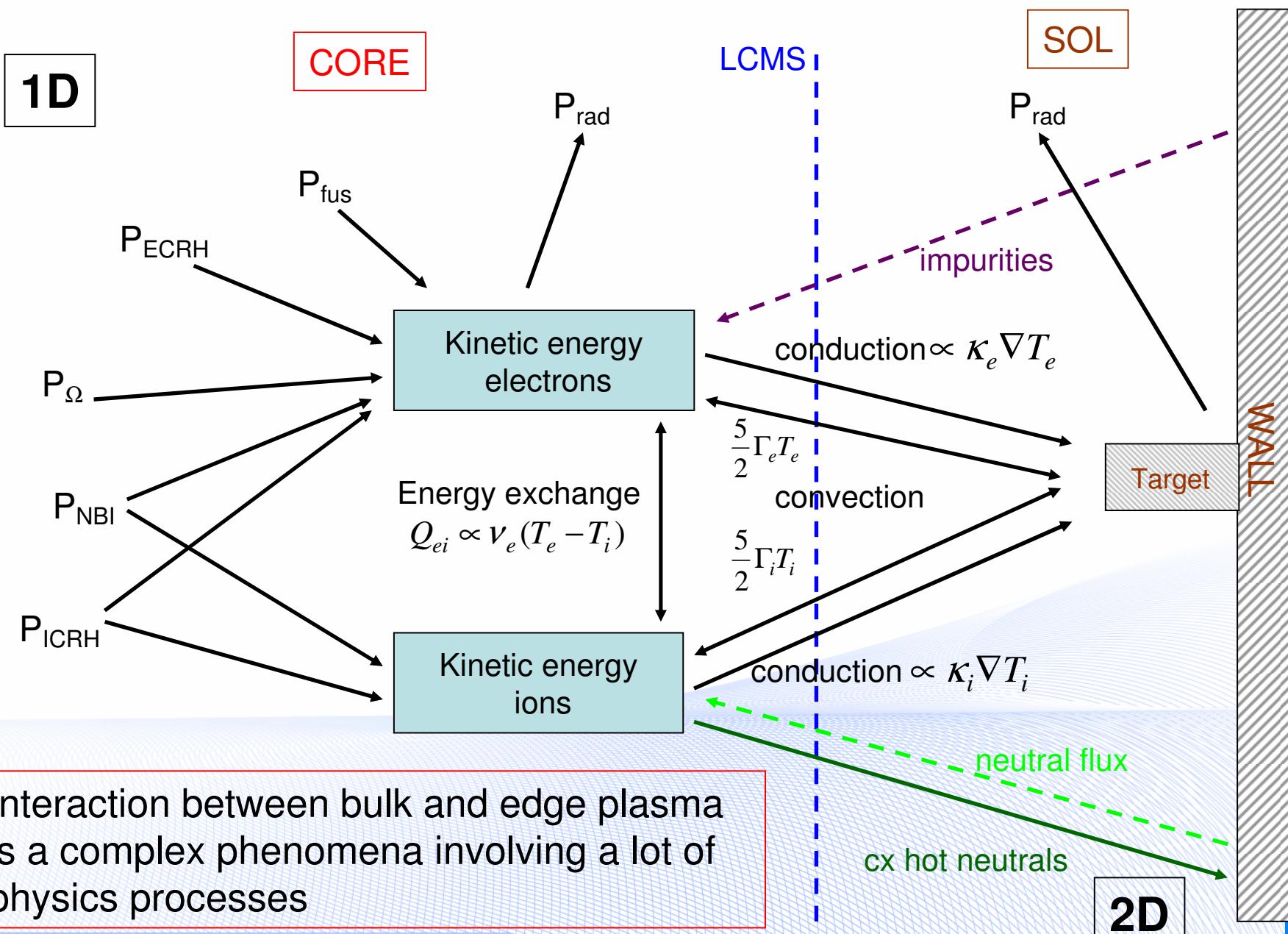
TOOL

- Long experience in coupled core-edge modelling
- COREDIV code to investigate integrated tokamak scenarios has been developed

AIM

- Comparison of the COREDIV code results with AUG experimental data

INTERPLAY BETWEEN EDGE AND CORE



In order to be able to treat simultaneously both plasma regions, core and edge, the COREDIV code was developed

COREDIV = 1D transport in the core self-consistently coupled to 2D model in the SOL

- It follows our experience with simpler self-consistent models (0D + 1D) successfully used to simulate FTU plasmas
- Aims at steady state description of plasmas with impurities

Basic elements of the coupled core-edge model

In order to describe the core and edge plasma self-consistently the following items has to be considered:

- Equations and transport model for the core
- Equations and transport model for the SOL
- Sources and boundary conditions
 - ❖ Atomic processes
 - ❖ PWI processes
 - ❖ Neutrals
 - ❖ Heating
 - ❖ Fueling
- Numerical code solving self-consistently transport in both regions

Equations and transport model for the **core plasma** - Background ions

1D transport of particles (n_i) and energy (T_e, T_i):

$$\frac{\partial n_i}{\partial t} + \frac{1}{rg_1} \frac{\partial}{\partial r} \left[rg_2 \left(-D_i \frac{\partial n_i}{\partial r} + w_i n_i \right) \right] = S_i(r) = S_i^0 \times P(r) + neocl. contrib.$$

$$\frac{3}{2} \frac{\partial n_i T_i}{\partial t} + \frac{1}{rg_1} \frac{\partial}{\partial r} \left[rg_2 \left(-k_i \frac{\partial T_i}{\partial r} + \frac{5}{2} \Gamma_i T_i \right) \right] = P_{AUX}^i + Q_{ei}$$

$$\frac{3}{2} \frac{\partial n_e T_e}{\partial t} + \frac{1}{rg_1} \frac{\partial}{\partial r} \left[rg_2 \left(-k_e \frac{\partial T_e}{\partial r} + \frac{5}{2} \Gamma_e T_e \right) \right] = P_{OH} + P_{AUX}^e + P_\alpha - P_B - P_{cyc} - P_{lin} - P_{ion} - Q_{ei}$$

S_i^0 iterated to have constant $\langle n_e \rangle$

Quasineutrality:

$$n_e = n_i + \sum_{k,j} n_j^k \quad \langle n_e \rangle = const. \quad i=D,T$$

Equations for plasma rotation and plasma current neglected \rightarrow
 $j(r)$ – given input function

g_1, g_2 – metric coefficients

Transport model for background ions

Anomalous transport described by simple model:

τ_E from experimental ELMy H-mode scaling

$$\chi_e^{an} = C_e \frac{a^2}{\tau_E} F(r)$$

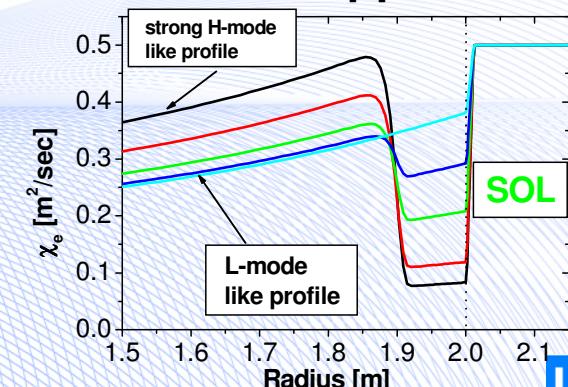
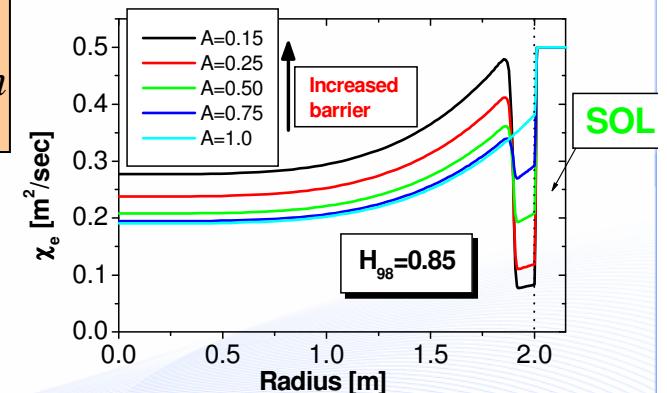
$$\chi_i^{an} = \chi_e^{an} \quad D_i^{an} = 0.1 \chi_e^{an}$$

C_e – adjusted iteratively to keep prescribed confinement

Anomalous pinch $V_{pinch}/D_i \sim r/a^2$

$F(r)$ – profile function

$$F(r) = \left(0.25 + 0.75 \left(\frac{r}{a} \right)^4 \right)$$



Impurity ions

- Different types of impurities are treated simultaneously and self-consistently

$$\frac{\partial n_j^k}{\partial t} + \frac{1}{rg_1} \frac{\partial}{\partial r} (rg_2 \Gamma_j^k) = n_e [n_{j-1}^k \alpha_{ion,k}^{j-1} - n_j^k (\alpha_{ion,k}^j + \beta_{rec,k}^j) + n_{j+1}^k \beta_{rec,k}^{j+1}] \quad j=1,\dots,Z_k$$

$$\Gamma_j^k = \cancel{\Gamma_j^{nc,k}} + \Gamma_j^{an,k}$$

High Z impurity accumulation

Pfirsch-Schlüter contribution

$$\Gamma_j^{nc} = -D_j^{PS,k} \partial n_j^k / \partial r + n_j^k W_j^{PS,k} = (1+q^2) \rho_k^2 v_j^k \left[-\frac{\partial n_j^k}{\partial r} + Z_j \left(\frac{1}{n_i} \frac{\partial n_i}{\partial r} - \frac{1}{2T_i} \frac{\partial T_i}{\partial r} \right) \right]$$

Anomalous contribution

$$\Gamma_j^{an,k} = -D_j^{an,k} \partial n_j^k / \partial r + n_j^k V_j^{pinch,k}$$

$$V_j^{pinch,k} \propto -\tau_E^2 D_j^{an,k} r / a^2$$

Usually anomalous transport same as for background plasma (ambipolarity)

$$D_j^{an,k} = D_i^{an}$$

IPP

Neutrals

(hydrogen, impurity) calculated from simple analytical model:

- exponential decay of neutral density from the separatrix
- e-folding length - function of plasma parameters

$$N_H(r) = N_H^{sep} \times \exp[-(a - r)/\lambda_{pen}(r)]$$

$$\lambda_{pen}(r) = \frac{\sqrt{2T_H/m_H}}{n_e \sqrt{\alpha_{ion}^H \alpha_{cx}^H}}$$

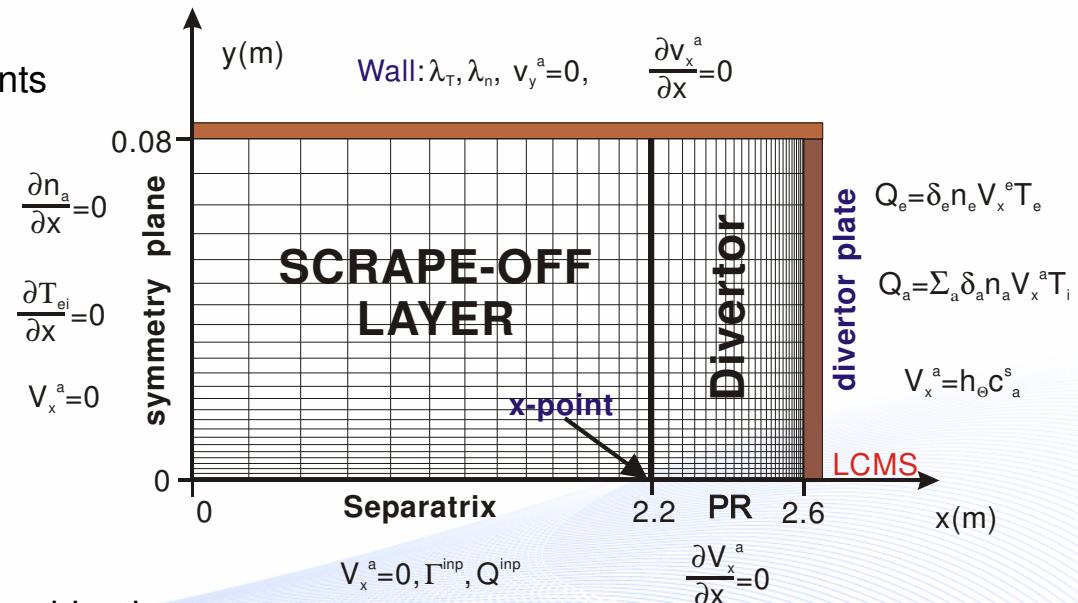
Coupling with the SOL plasma through the boundary conditions at the separatrix:

n_i, n_z, T_e, T_i – from SOL model

P_{inp}, Γ_{inp} – calculated from core model

BASIC MODEL ASSUMPTIONS OF 2D SOL MODEL

- **2D MULTIFLUID DESCRIPTION OF PLASMA** - Braginskij-like equations
- **CLASSICAL TRANSPORT ALONG FIELD LINES** (21 - moment Grad approximation)
- **RADIAL TRANSPORT:**
anomalous: constant diffusion coefficients
- **TWO TEMPERATURE MODEL**
all ions have common temperature
- **DRIFTS AND CURRENTS NEGLECTED**
- **ATOMIC PROCESSES:** ionization, recombination, excitation, charge exchange
- **NEUTRALS** (Analytical model for neutrals accounts for plasma recycling and impurity sputtering (also by seeded impurities). **Recycling is an external parameter**)
- **MAGNETIC TOKAMAK GEOMETRY (SLAB MODEL)**



Continuity equation (particle balance):

$$\frac{\partial n_a}{\partial t} + \frac{1}{\sqrt{g}} \left(\frac{\partial}{\partial x} \frac{\sqrt{g}}{h_x} n_a V_{ax} + \frac{\partial}{\partial y} \frac{\sqrt{g}}{h_y} \Gamma_a \right) = S_n^a$$

$a = i, j \quad j = 1, Z_{\max}$ — atomic number

Diffusion equation

$$\Gamma_a \equiv n_a V_{ay} = -D_y^a \frac{1}{h_y} \frac{\partial n_a}{\partial y} + n_a V_{ay}^d$$

Equation of motion (momentum balance):

$$n_a m_a \frac{\partial \vec{V}_a}{\partial t} + n_a m_a \vec{V}_a \cdot \nabla \vec{V}_a + \operatorname{div} \vec{\Pi}_a = -\nabla p_a + n_a e_a (\vec{E} + \vec{V}_a \times \vec{B}) + \vec{R}_a + (\vec{S}_V^d - m_a \vec{V}_a S_n^a)$$

Electron temperature equation

$$\frac{3}{2} \frac{\partial n_e T_e}{\partial t} + \nabla \cdot \left(\frac{5}{2} n_e \vec{V}_e T_e + \vec{q}_e \right) = r.h.e + S_E^e$$

Ion temperature equation ($\varepsilon_a = \frac{1}{2} n_a m_a \vec{V}_a^2$):

$$\frac{\partial}{\partial t} \sum_a \left(\frac{3}{2} n_a T_i + \varepsilon_a \right) + \nabla \cdot \sum_a \left(\frac{5}{2} n_a \vec{V}_a T_i + \vec{V}_a \varepsilon_a + \vec{q}_a + \vec{V}_a \cdot \vec{\Pi}_a \right) = \sum_a r.h.a + \sum_a S_E^a$$

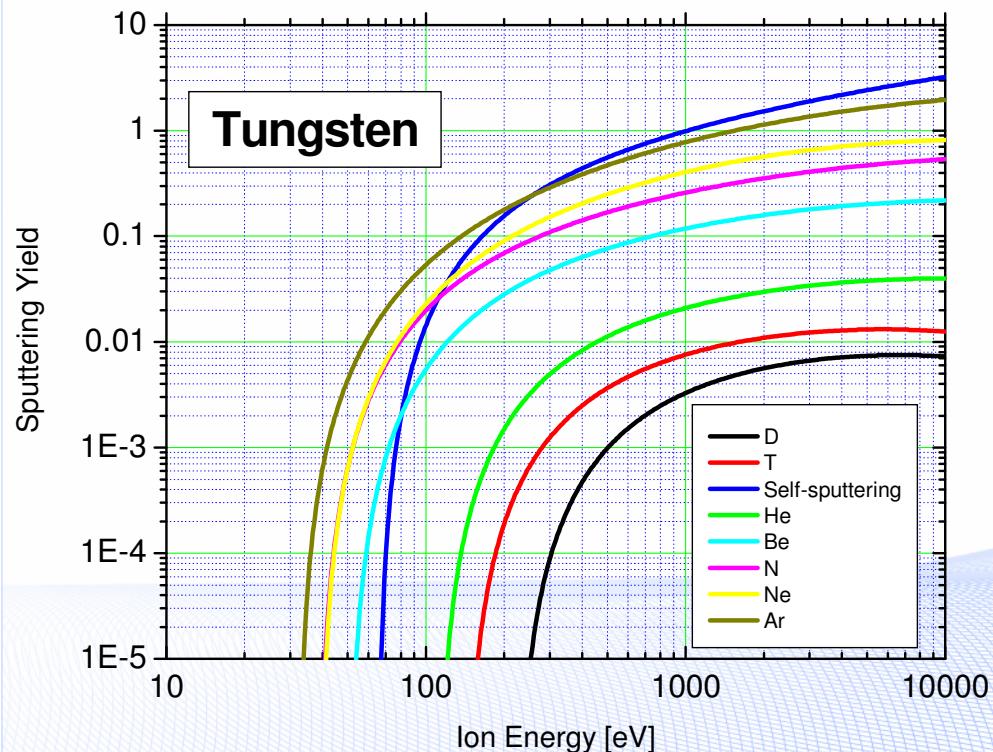
The right hand sides have the form:

$$r.h.e = -en_e \vec{V}_e \cdot \vec{E} + \vec{R}_e \cdot \vec{V}_e + Q_e$$

$$\sum_a r.h.a = \sum_a e_a n_a \vec{V}_a \cdot \vec{E} + \sum_a \vec{R}_a \cdot \vec{V}_a + \sum_a Q_a = \vec{j} \cdot \vec{E} - r.h.e.$$

SOL plasma

- Boundary conditions:
sheath, decay lengths; input fluxes from the core part of the model
- Intrinsic and seeded impurities – gas puff at different positions



He, Li, Be, B, C, N, O, Ne, Si,
Ar, Ti, Ni, Mo, W

$$E_{ion} \approx (5 - 7) \times T_e$$

Tungsten sputtering yields

Main Limitations of the Model

- Slab geometry – one target plate
- No drifts
- Simple model for neutrals – detachment can not be modeled correctly
- Current density given (no evolution of magnetic field)
- Plasma rotation neglected

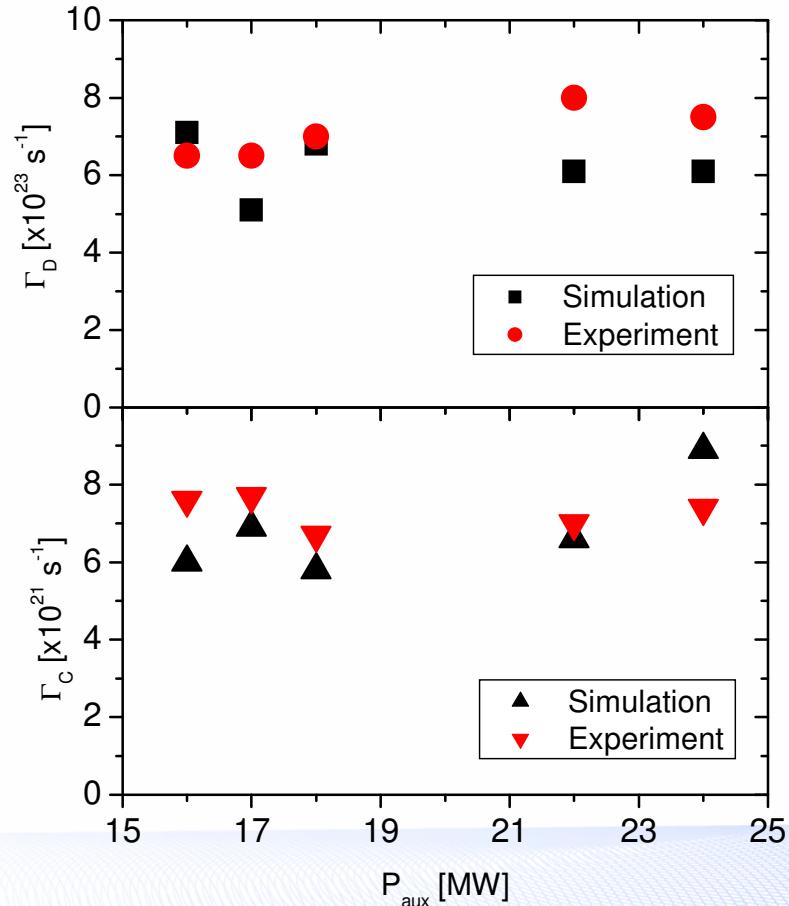
Benchmarking of the code

COREDIV checked against a number of JET discharges:

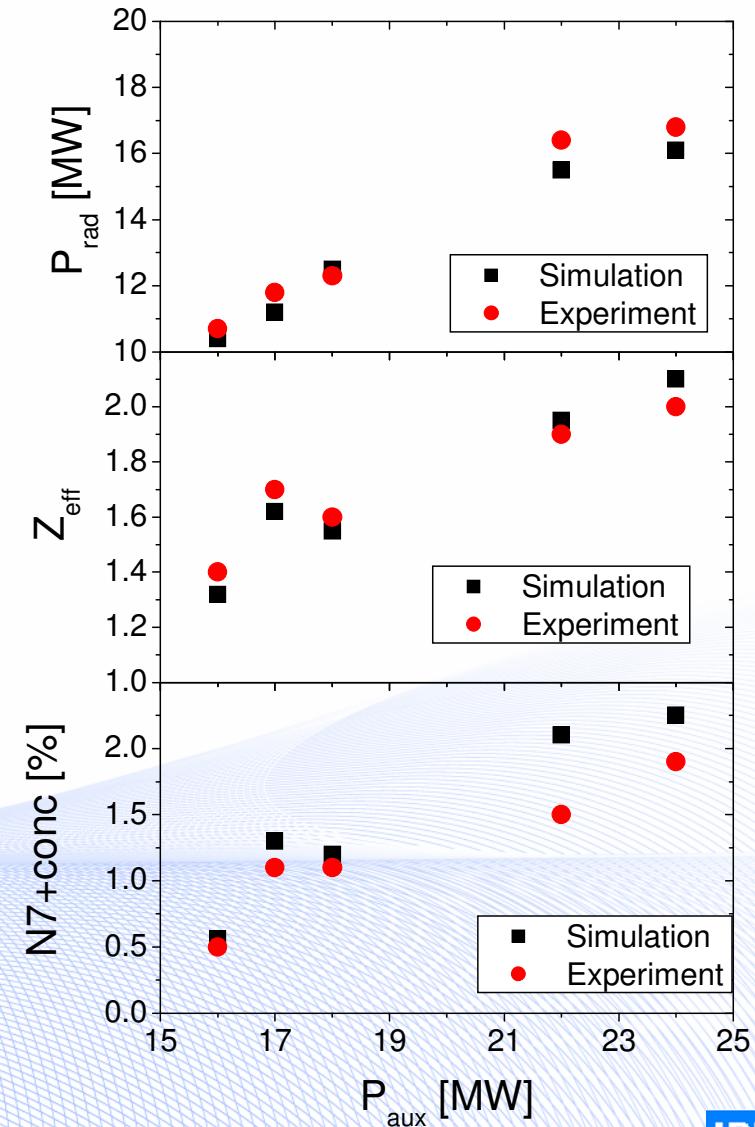
- **Type I ELM My JET discharges with Nitrogen and Neon seeding**
- **Type III ELM My JET discharges with Nitrogen seeding**
- **JET AT (advanced tokamak) scenarios with Neon seeding**

Benchmarking of the COREDIV code

Simulations of Type III ELM My JET discharges with Nitrogen seeding



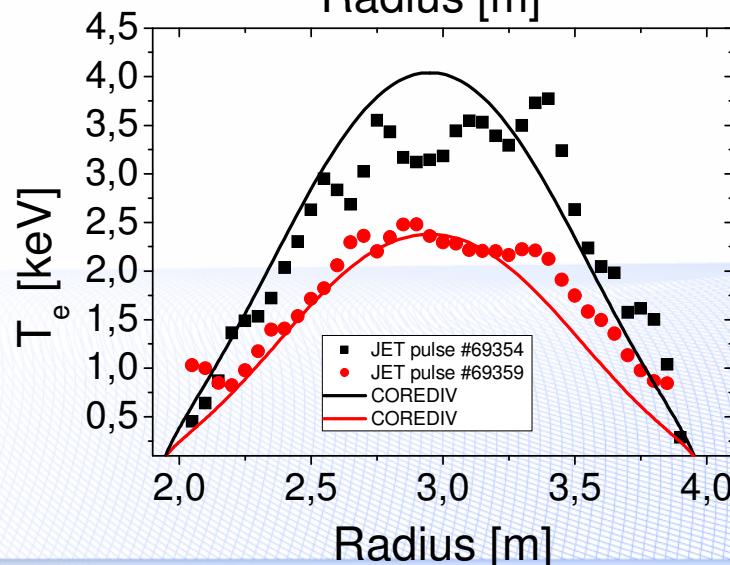
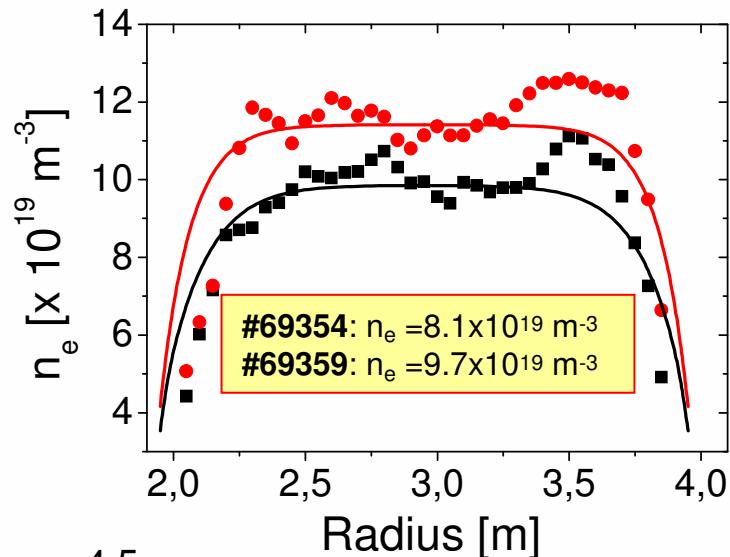
Power scan



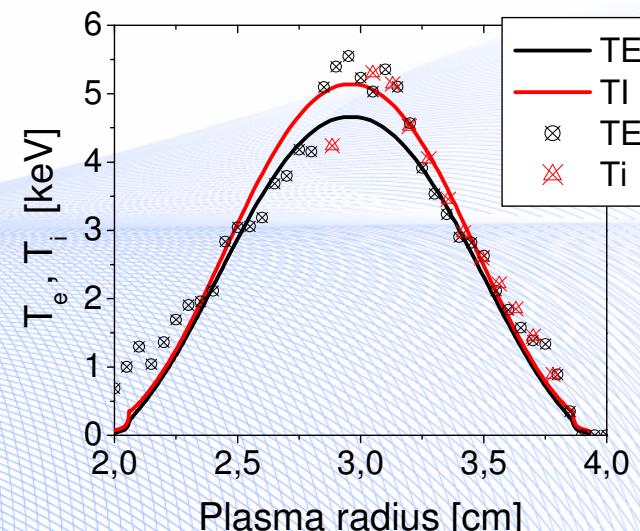
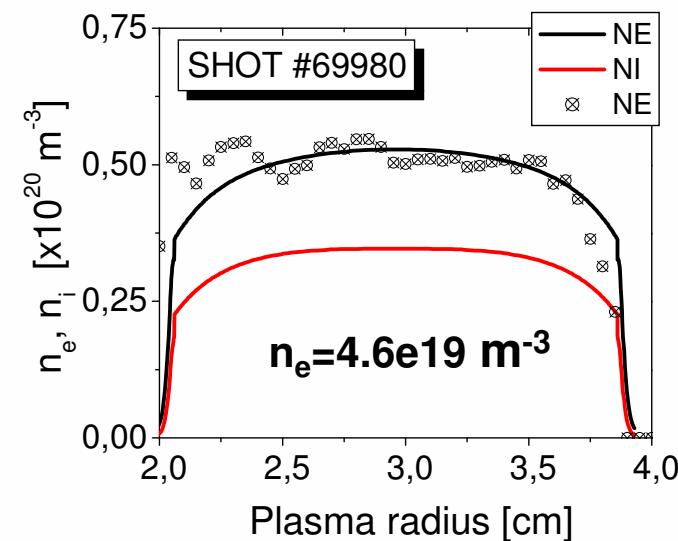
IPP

Benchmarking of the COREDIV code

Type III ELM My JET discharges with N₂ seeding (q=3)



Neon seeded AT scenarios (B_T=3.1 T, I_p=1.9 MA, q=5)



Simulations of Nitrogen seeded AUG discharges

To justify prediction results for ITER and JET ILW
comparison with plasma parameters in a full W environment necessary

Simulations of Nitrogen seeded AUG discharges

- ❖ 18 shots out of 49
- ❖ 3 different scans selected (power and density scans)
- ❖ Two shots selected (without nitrogen) to fix the code parameters: n_{sep} , $D_{perp}=0.25 \text{ m}^2/\text{s}$, $D_z=D_{perp}$, low Z impurity level $\rightarrow \Gamma_C$

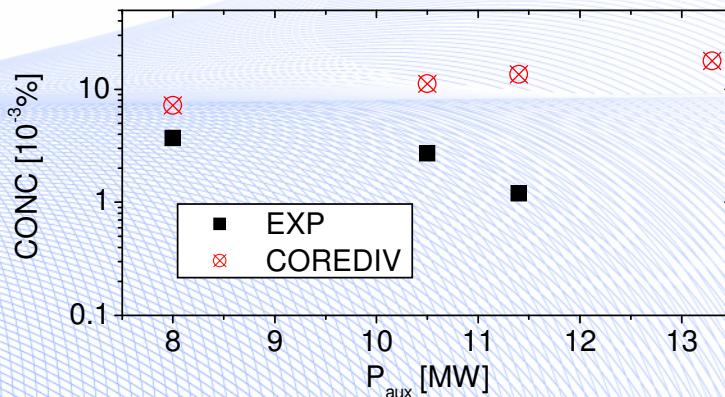
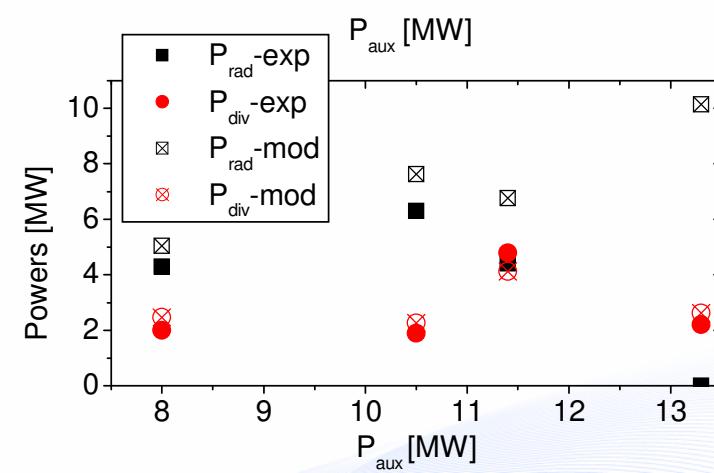
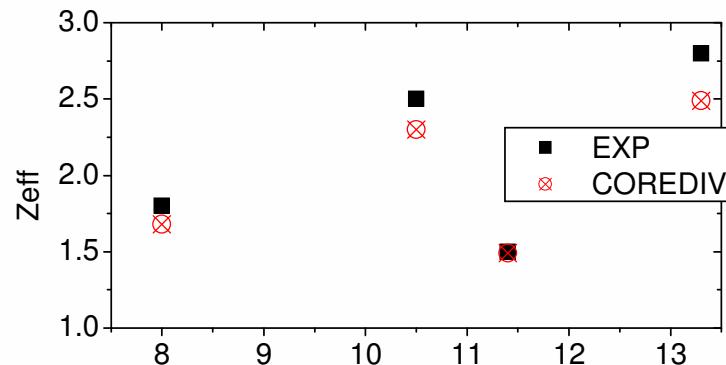
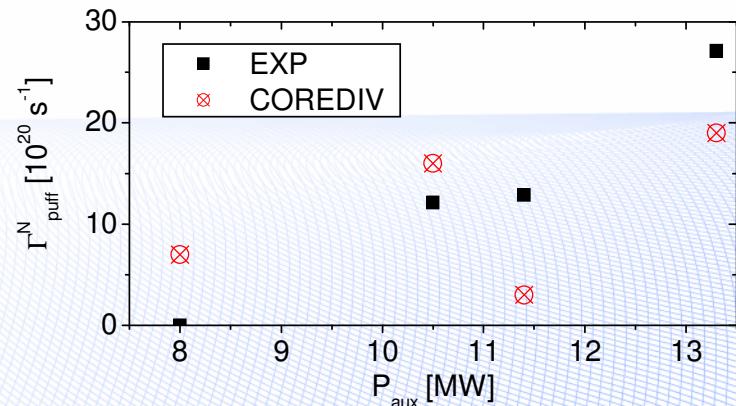
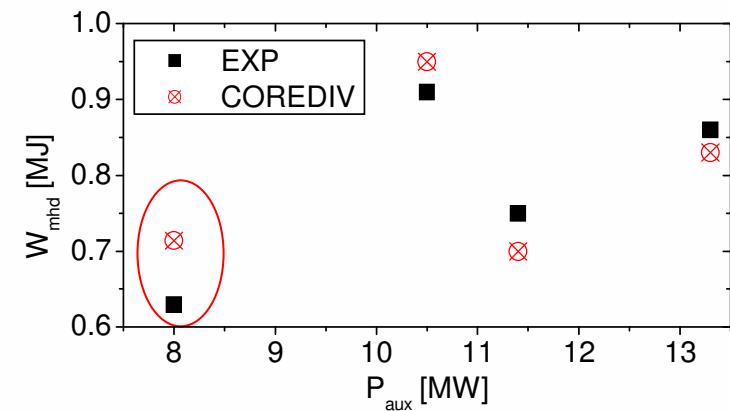
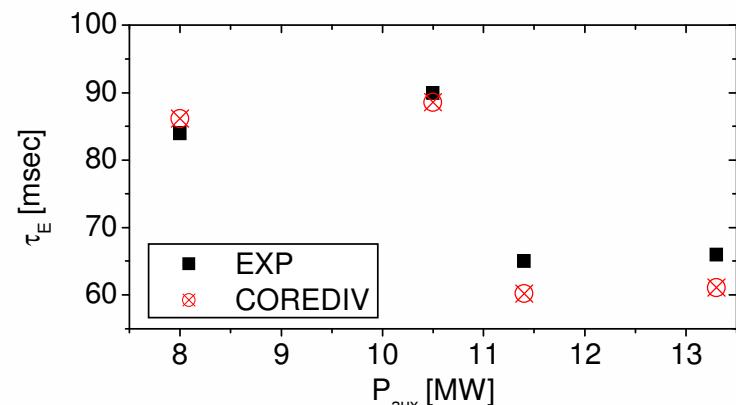
Assumptions:

- Constant carbon influx: $\Gamma_C = 5.5 \times 10^{20} \text{ s}^{-1}$
- Minimum nitrogen seeding $\Gamma_N > 1 \times 10^{20} \text{ s}^{-1}$ (nitrogen legacy effect)
- Transport with edge barrier (5 cm, $A=0.15$)
- $n_{sep} = 0.5 <n_e>$ the hydrogen recycling coefficient ($0 < R_H < 1$) was iterated accordingly
- The same geometry for all simulations ($a=60 \text{ cm}$)
- $P_e^{aux}/P_i^{aux} = 3/1$

Selected experimental shots

Shot#	t (s)	Paux (MW)	D-puff rate (1E+2 1e/s)	N-puff rate (1E+21e /s)	divertor temperature - Te (eV)	time averaged W-nflux (1E16/m^2s)	W concen trat. (edge) 0.00001	W concen trat centre) 0.00001	Bt (T)	ne (1e19/m^3)	nsep (1e19/m^3)	Prad (MW)	Wm hd (MJ)	Zeff	tau (ms)	H98	Pdiv (MW)
25366	5.5	13.3	8	19	7	5.5	0	0	2.42	8.3	3.1	0	0.86	2.8	66	0.94	2.2
25707	3	11.4	10	9	9	2.6	1.2	1.2	2.49	8.3	3	4.4	0.75	1.5	65	0.83	4.8
24682	4.5	10.5	8	8.5	7	23	2.7	2.7	2.46	8.4	3	6.3	0.91	2.5	90	1.15	1.9
24681	3.7	8	8	0	12	11	3.7	3.7	2.46	8.3	3	4.3	0.63	1.8	84	0.94	2
23223	5	13.6	0	0	29	41	1	1.4	2.54	7.1	1.6	5	1	1.6	72	1	6.3
25393	4.5	10.8	8	11.7	7	5.4	2.8	4.7	2.61	7.5	0	5.7	0.84	2.2	82	1.05	2.1
25367	3.5	8.3	8	9	5.5	2.9	1.8	2.4	2.43	7.5	2.3	4.4	0.71	2	90	1.04	1.7
25391	3.5	8.2	8	9	8	2.9	2.7	4	2.57	7.5	2.2	4.1	0.64	1.7	86	0.97	0
25392	3.5	7.5	8	8.8	5	3.2	2.4	3	2.57	7.5	2.4	4.6	0.68	1.9	86	0.99	1.4
23223	2.7	6.2	0	0	12	16	0.6	0.8	2.54	7.5	1.4	2.2	0.55	1.3	86	0.87	2.5
25354	2.7	5.7	8	8	9	2	0	0	2.47	7.5	2.1	3	0.54	1.7	96	0.94	1.2
25366	4.5	10.8	8	21	7	5.3	0	0	2.42	7.6	2.9	5.7	0.84	2.4	81	1.04	2.1
25367	4.5	10.8	8	14	6.5	4.6	2.2	3.3	2.43	7.7	2.4	5.6	0.89	2.4	85	1.11	2.3
25354	4.5	10.8	8	17	7	5.1	0	0	2.47	7.8	2.7	5.5	0.86	2.3	83	1.07	2.4
24681	5	10.5	8	0	13	20	2.7	2.7	2.46	8	2.7	4.9	0.74	1.9	74	0.94	3.6
24682	4.5	10.5	8	8.5	7	23	2.7	2.7	2.46	8.4	3	6.3	0.91	2.5	90	1.15	1.9
25392	5	10.8	8	16.5	4.6	4.5	3.3	6	2.57	8.4	2.9	6.5	0.83	2.5	79	1	1.6
25353	5	10.8	8	20	6.5	2.9	36	0	2.27	8.6	3.1	6	0.61	1.8	60	0.77	1.6

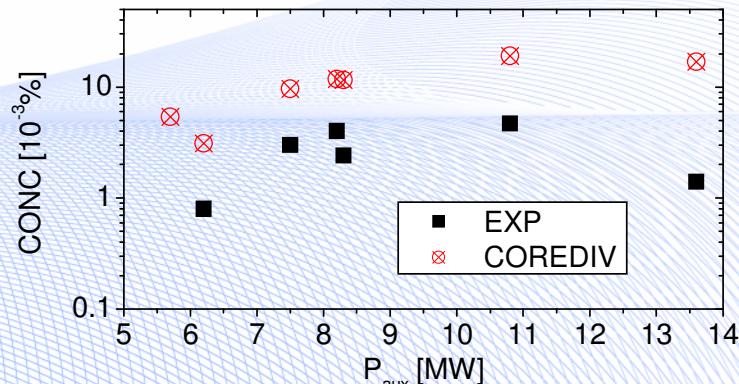
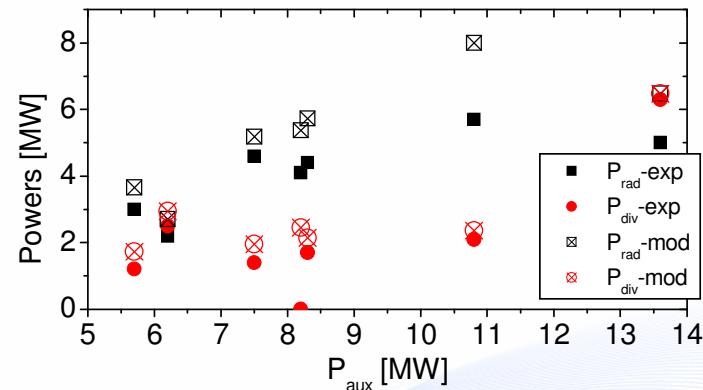
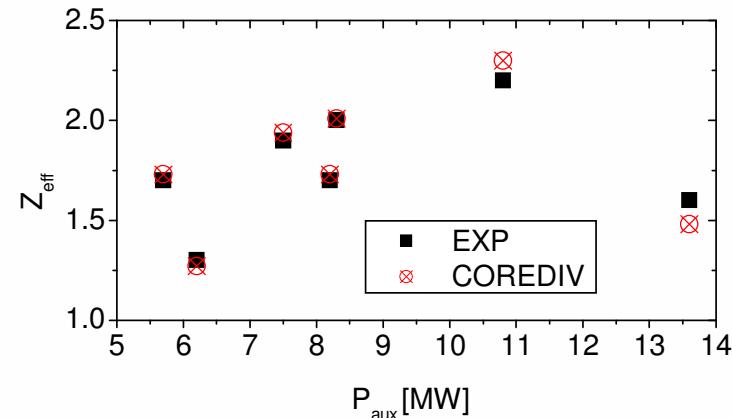
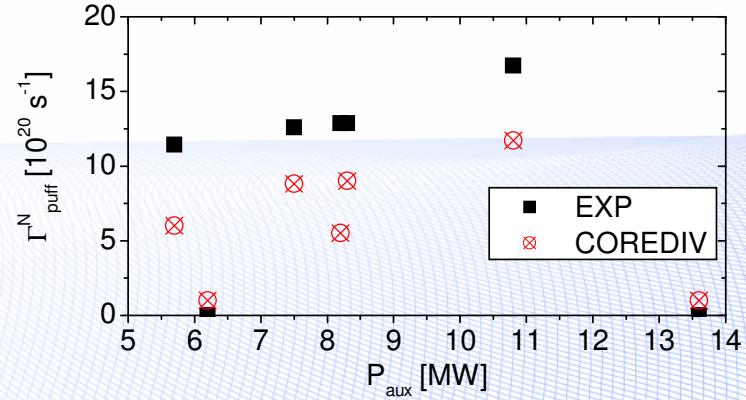
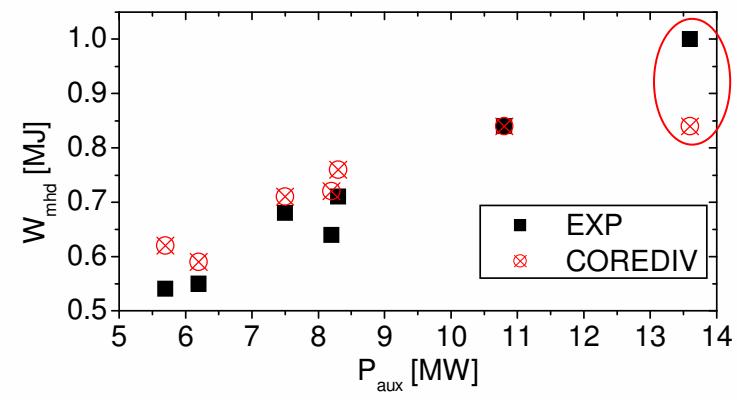
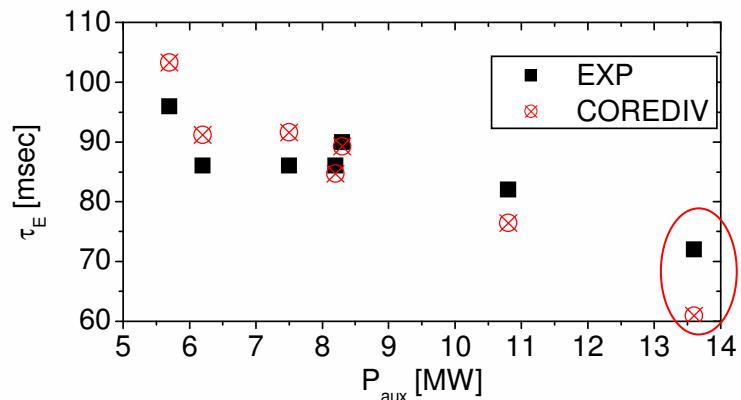


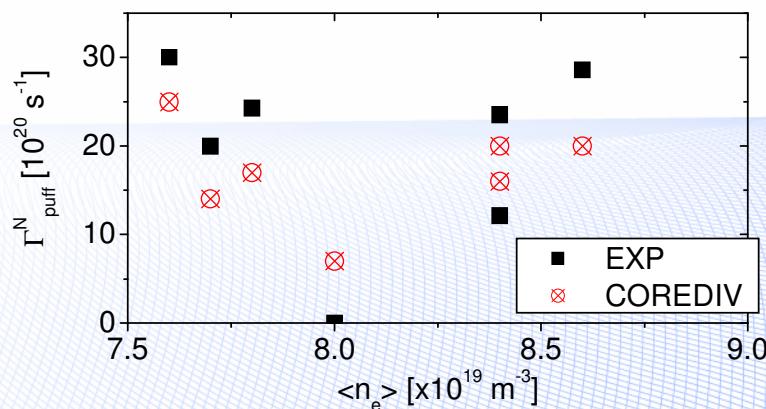
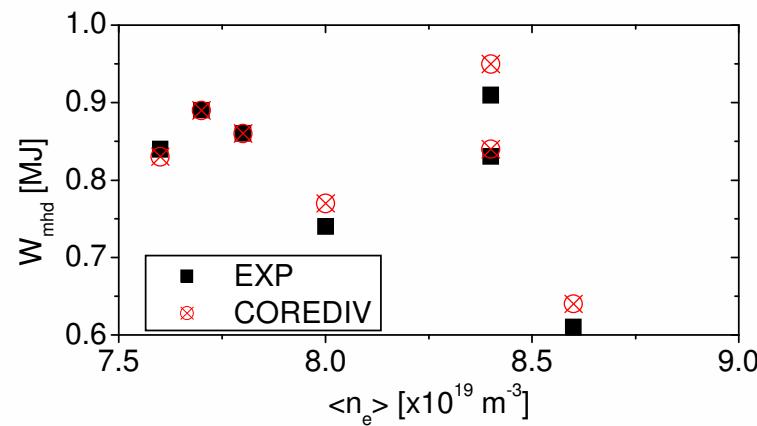
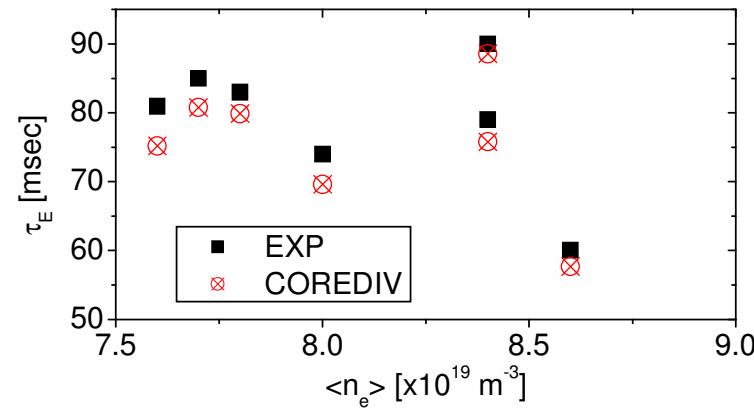
Power scan 1 - $\langle n_e \rangle = 8.3-8.4 \times 10^{19} \text{ m}^{-3}$ 



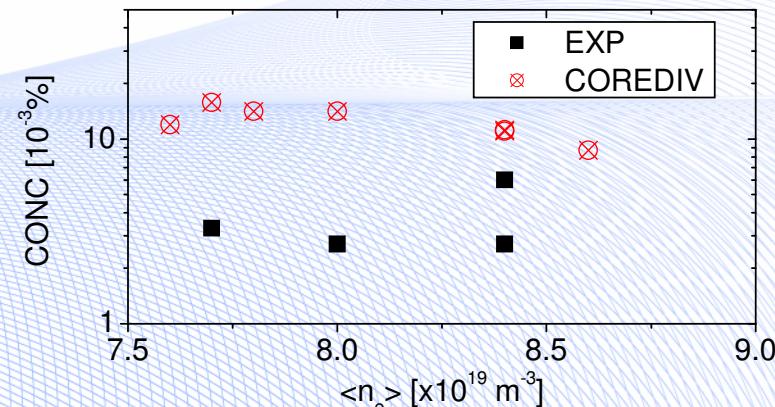
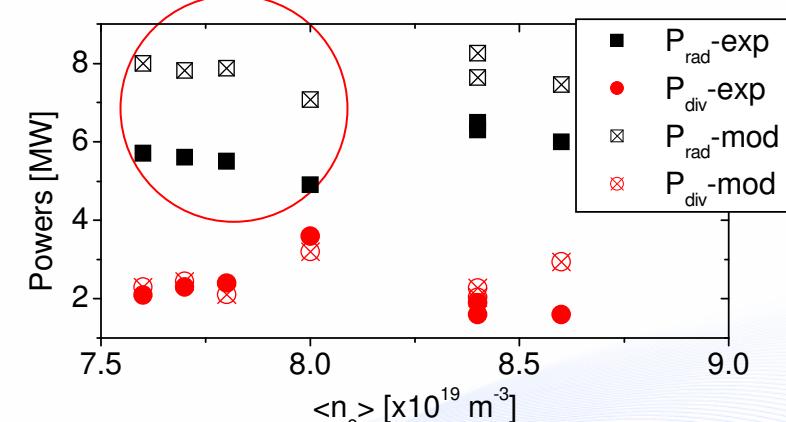
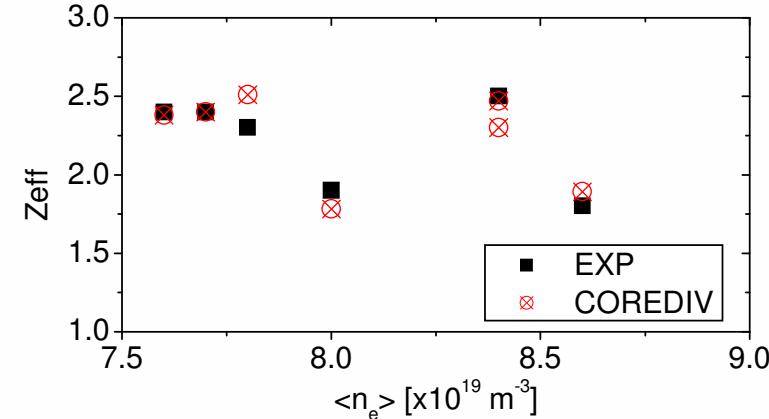
EFDA

EUROPEAN FUSION DEVELOPMENT AGREEMENT

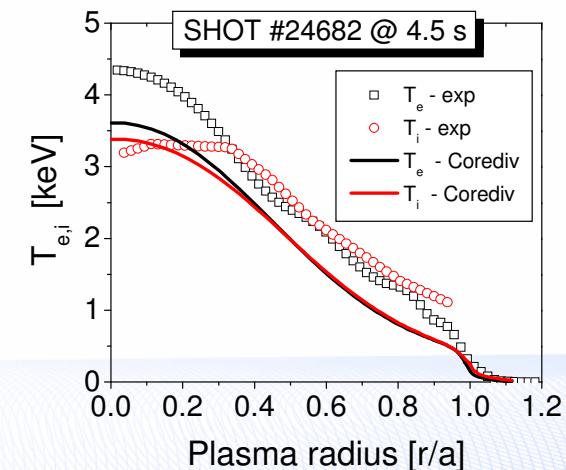
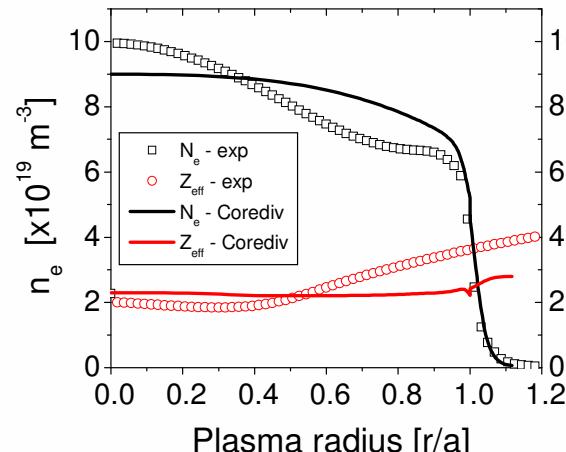
IPPLM
EURATOMPower scan 2 - $\langle n_e \rangle = 7.1-7.5 \times 10^{19} \text{ m}^{-3}$ 



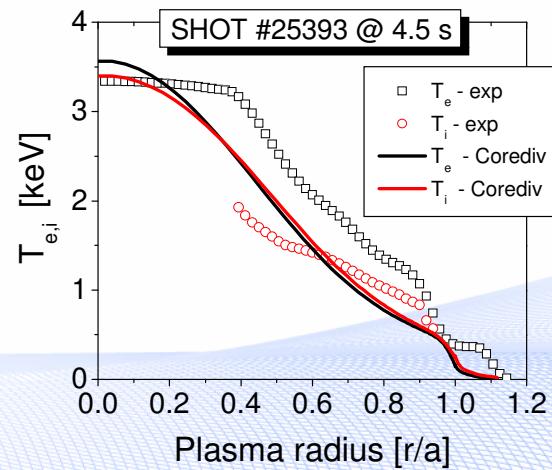
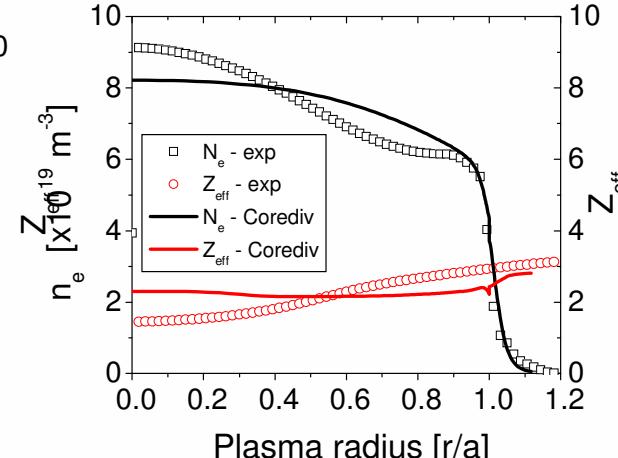
Density scan - P_{aux}=10.5-10.8 MW



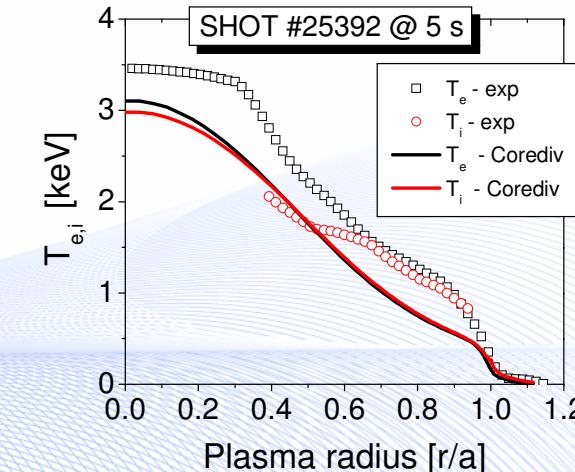
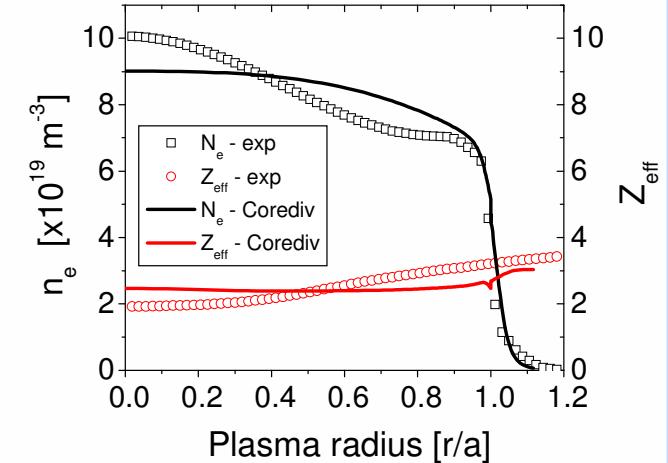
Comparison with experimental profiles



Power scan 1

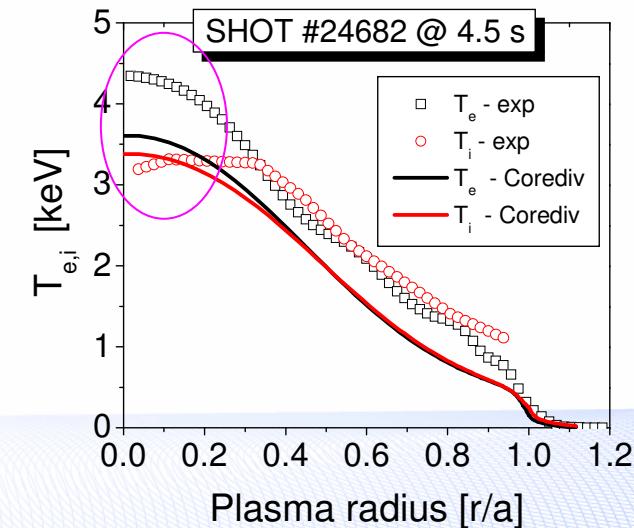
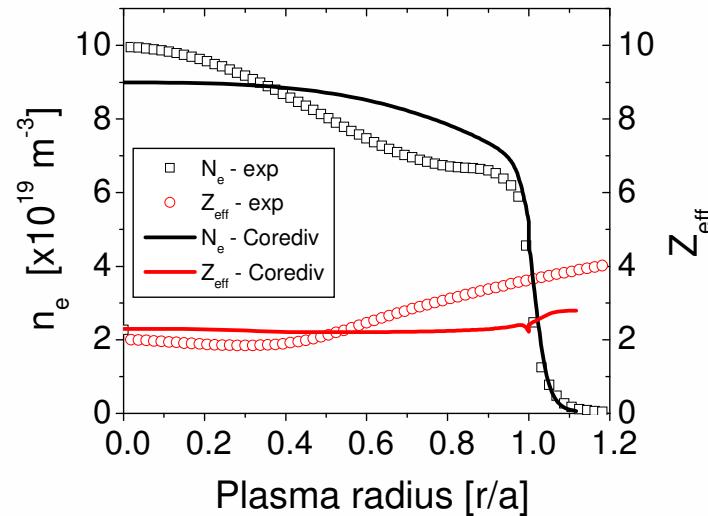


Power scan 2

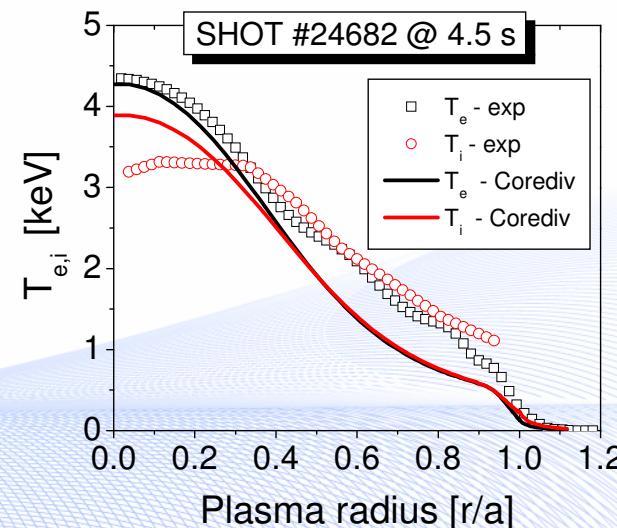
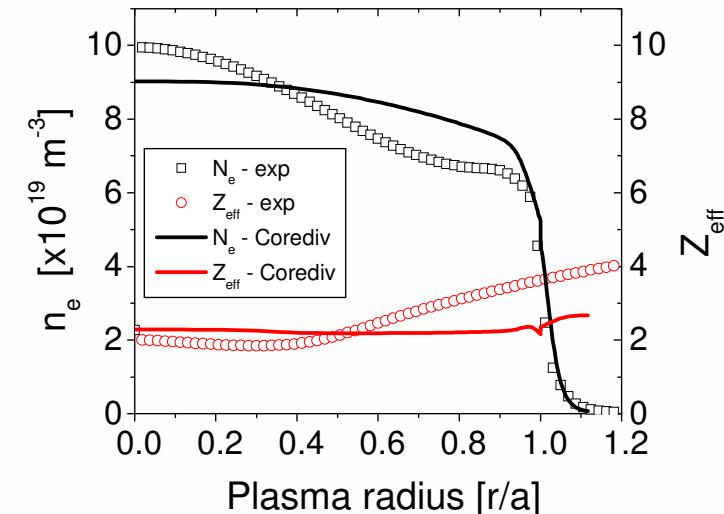


Density scan

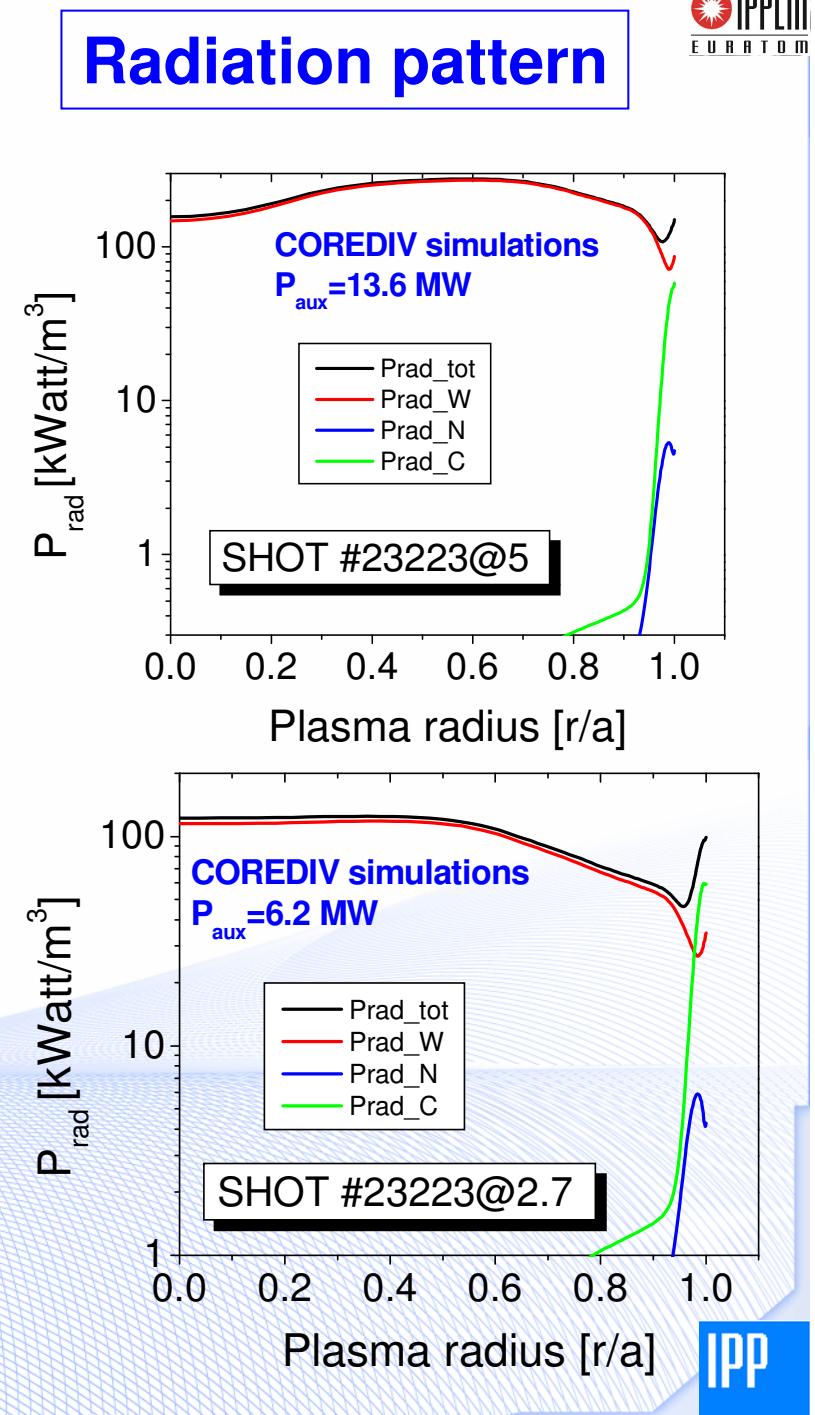
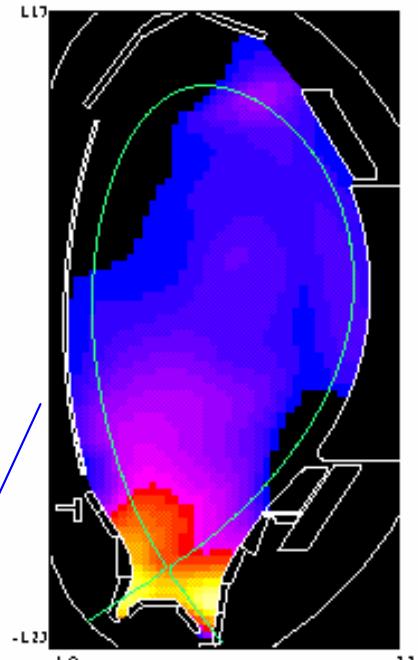
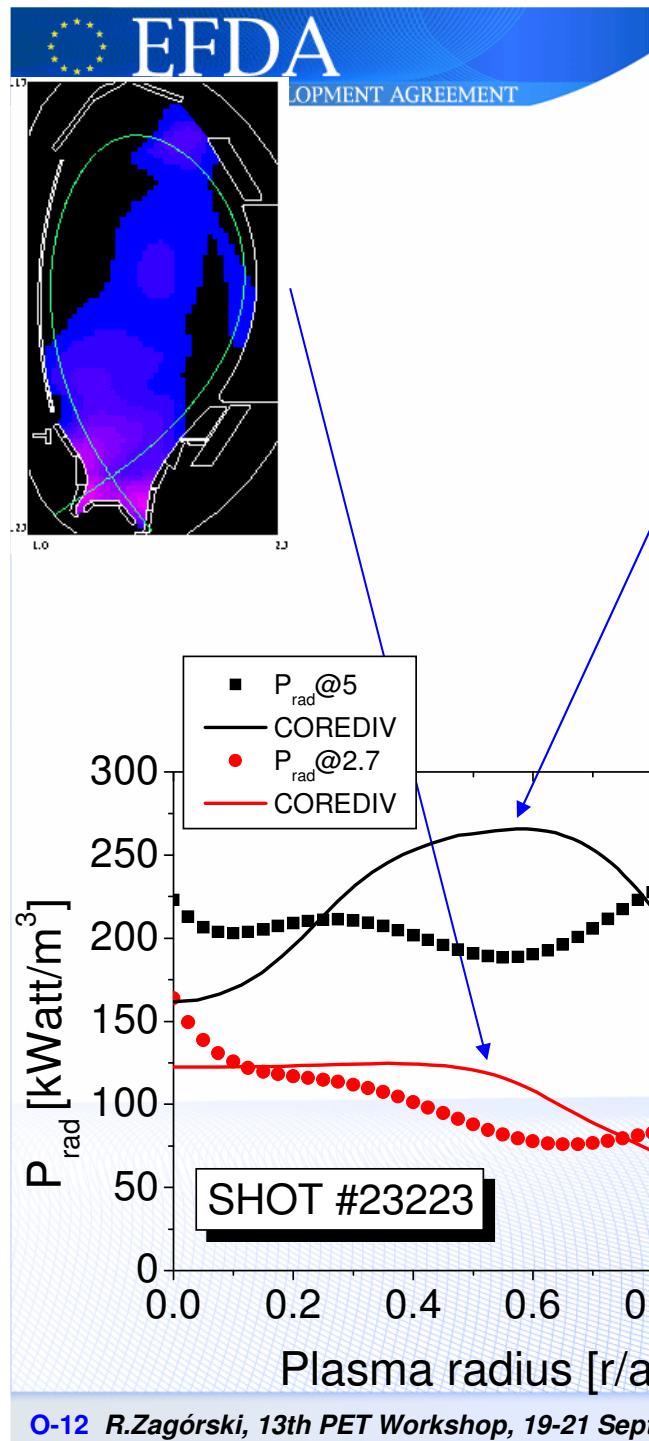
Improving the agreement with experiment



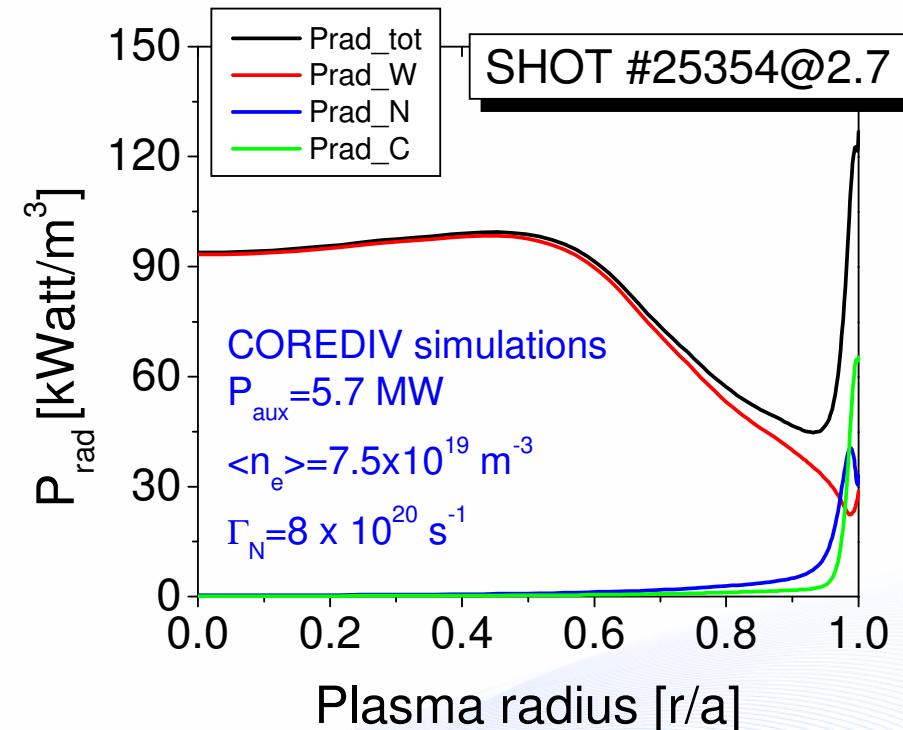
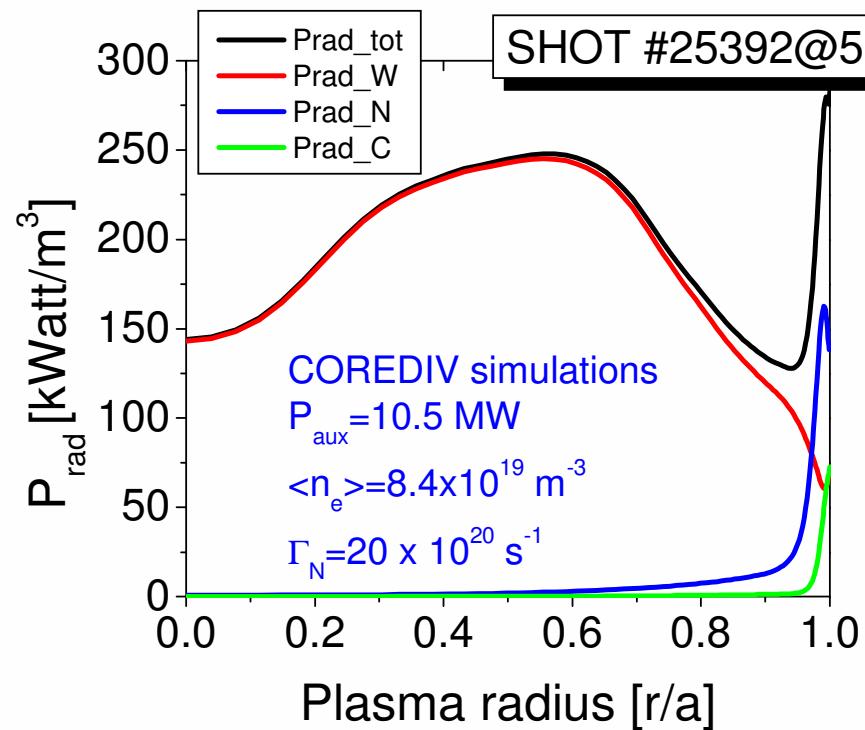
$$F(r) = \left(0.25 + 0.75 \left(\frac{r}{a} \right)^4 \right)$$



$$F(r) = \left(0.1 + 0.9 \left(\frac{r}{a} \right)^4 \right)$$



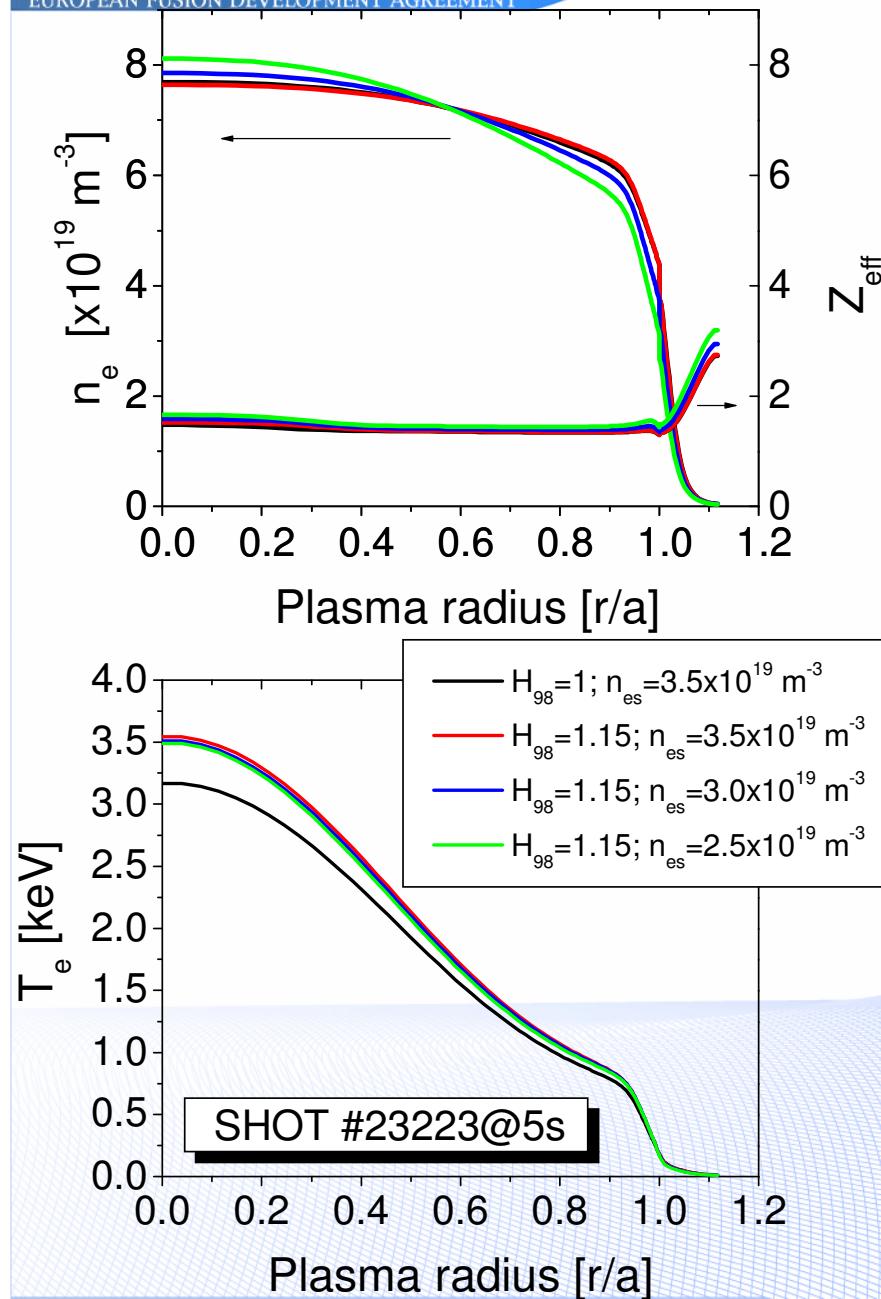
Radiation pattern



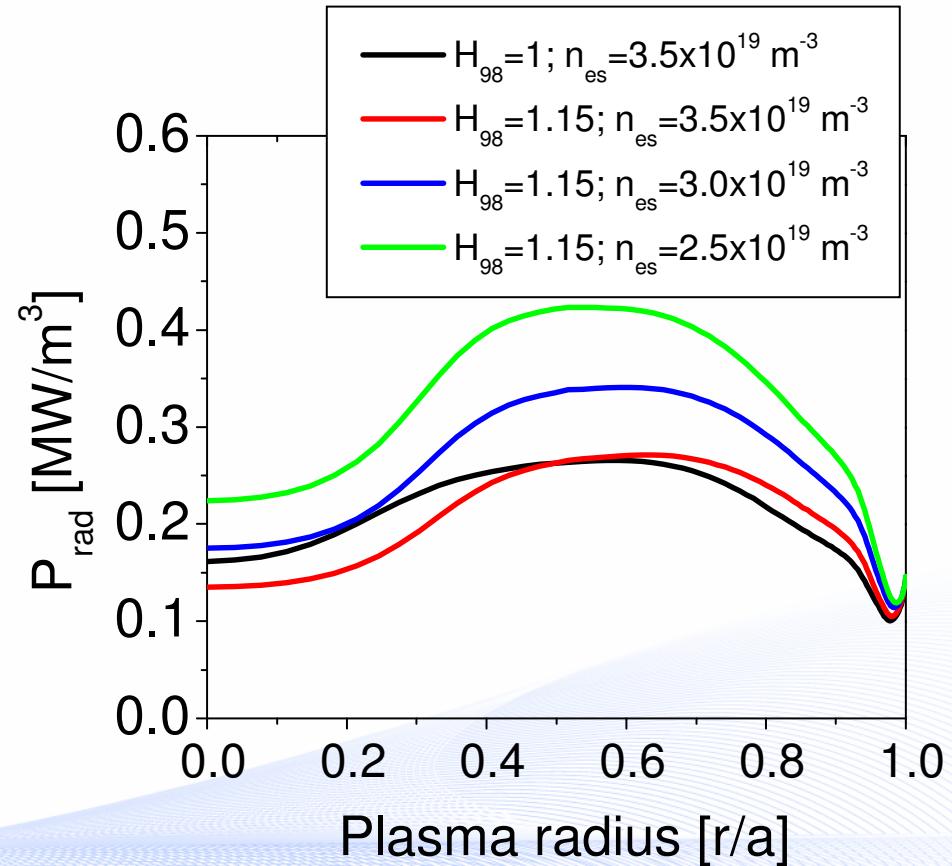
$P_{sol}=3.4 \text{ MW}$
 $P_{core}=4.85 \text{ MW}$

$P_{sol}=1.76 \text{ MW}$
 $P_{core}=1.89 \text{ MW}$

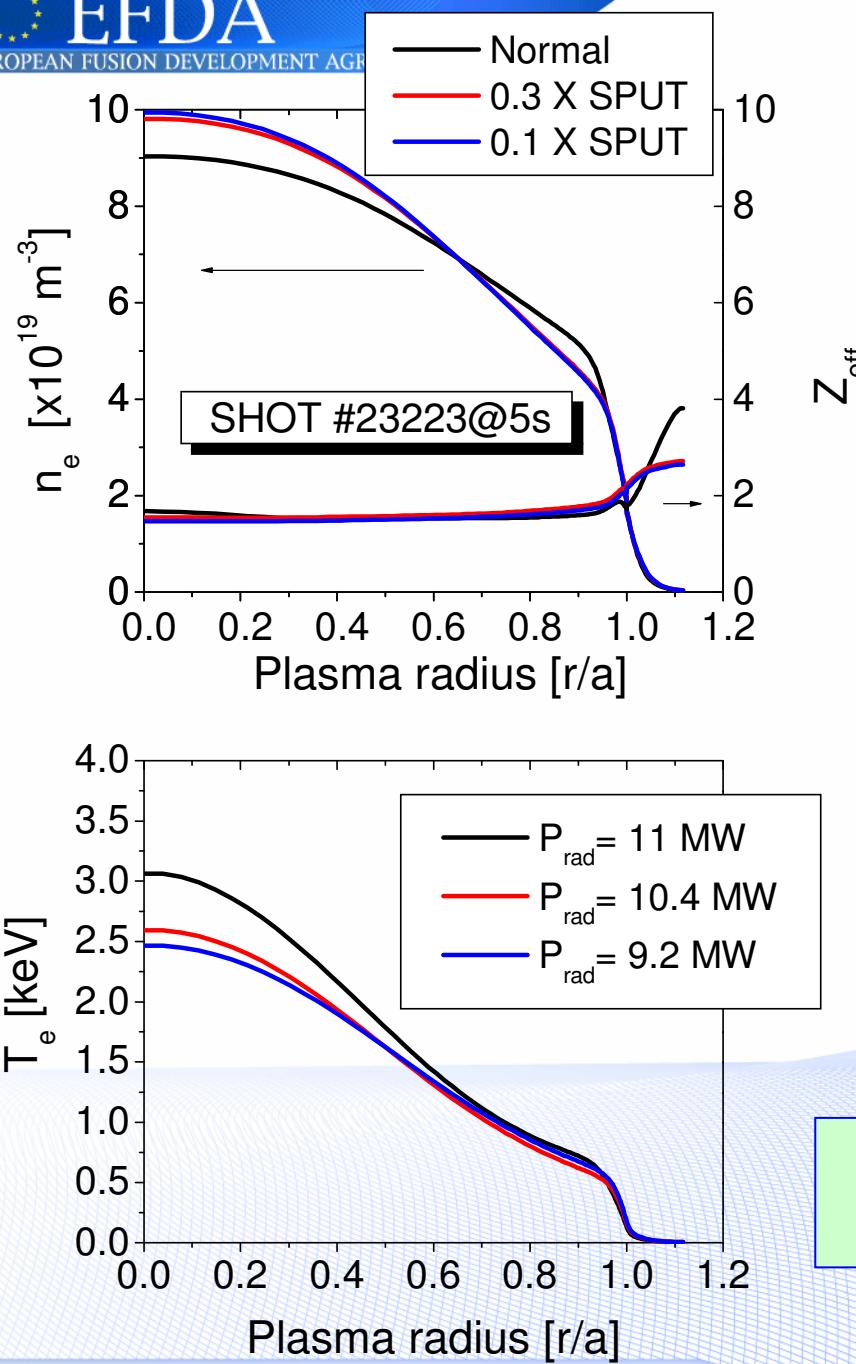
W radiation is the dominant energy loss mechanism in most cases



Effect of edge density



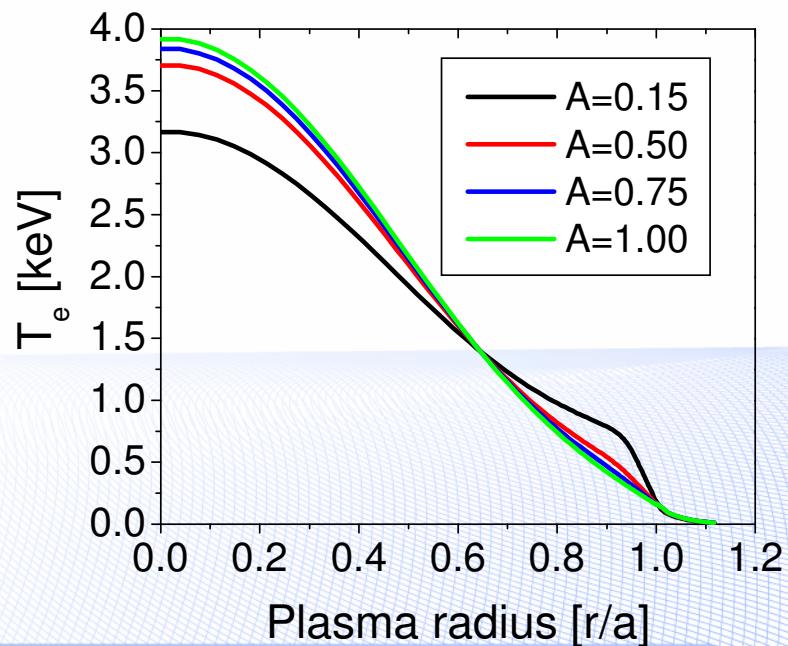
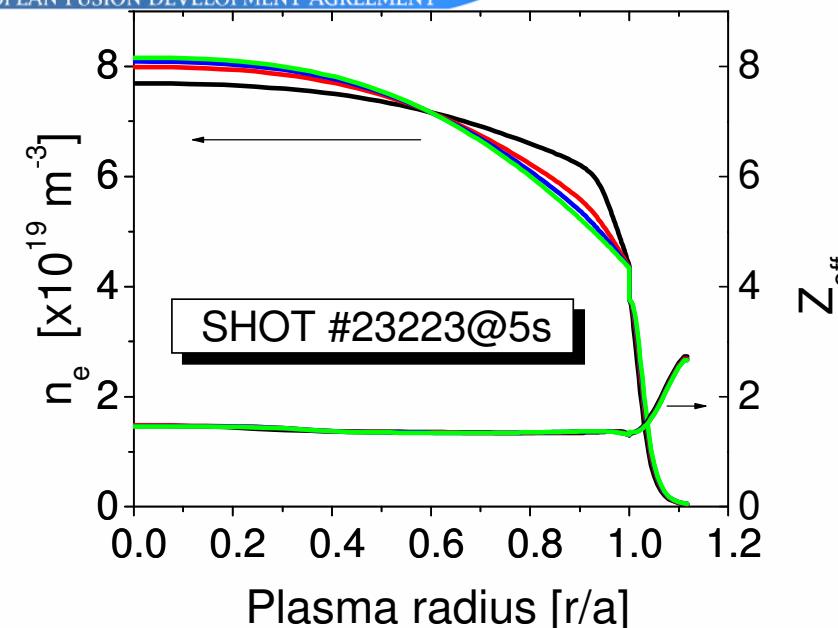
$n_{es} \downarrow \Rightarrow P_{\text{rad}} \uparrow$



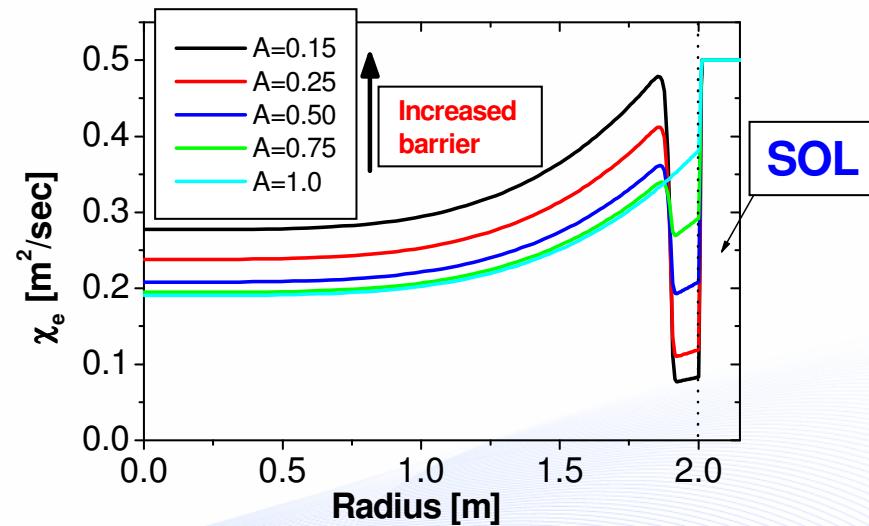
Effect of W sputtering

Sputtering	$T_{e, \text{plate}}$ [eV]	$N_{e, \text{plate}}$ [10^{20} m^{-3}]
Normal	18.7	1.2
x 0.3	60.7	0.18
X 0.1	82.8	0.14

Core parameters weakly affected by sputtering yield



Effect of transport barrier



- 1. Self-consistent COREDIV code applied to simulate AUG experimental data**
 - full W environment
 - nitrogen seeding
- 2. Global parameters reproduced by the code for majority of shots:**
 - Very good agreement with core global parameters
 - Not all experimental results steady state
 - Experimental energy balance not perfect
 - COREDIV shows significantly larger W concentrations (factor 3-10)
- 3. Plasma profiles reasonably simulated by the code:**
 - density and temperatures (COREDIV temperatures slightly lower)
 - Z_{eff}
 - plasma radiations
 - COREDIV shows that W radiation is the dominant energy loss mechanism in most cases
- 4. Simulations show that core-edge coupling is the primary mechanism determining the plasma parameters in AUG**

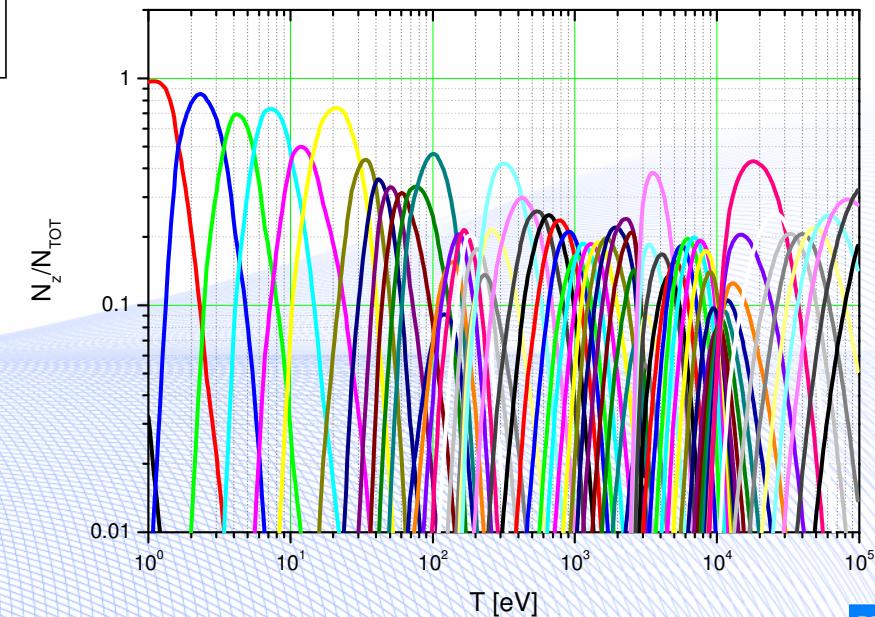
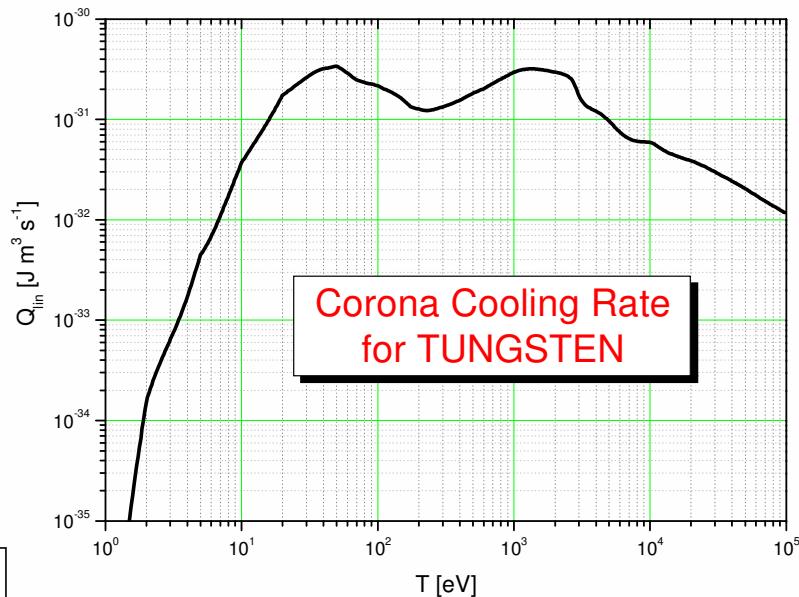
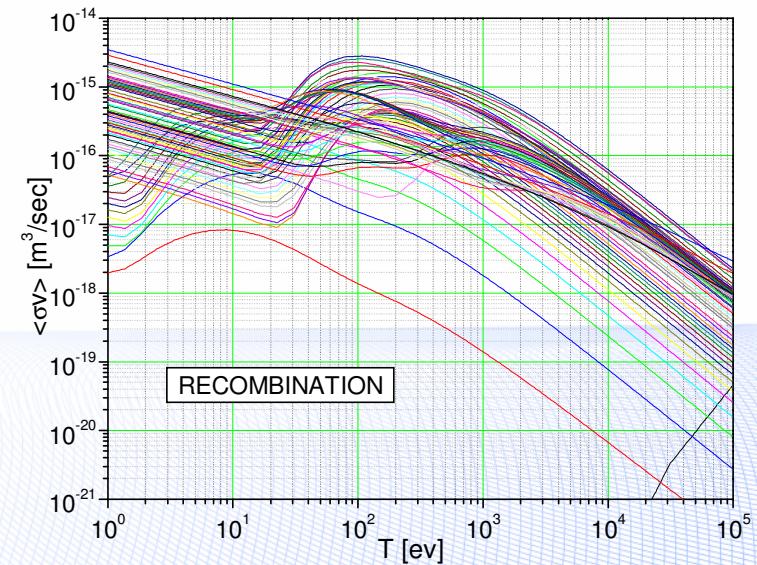
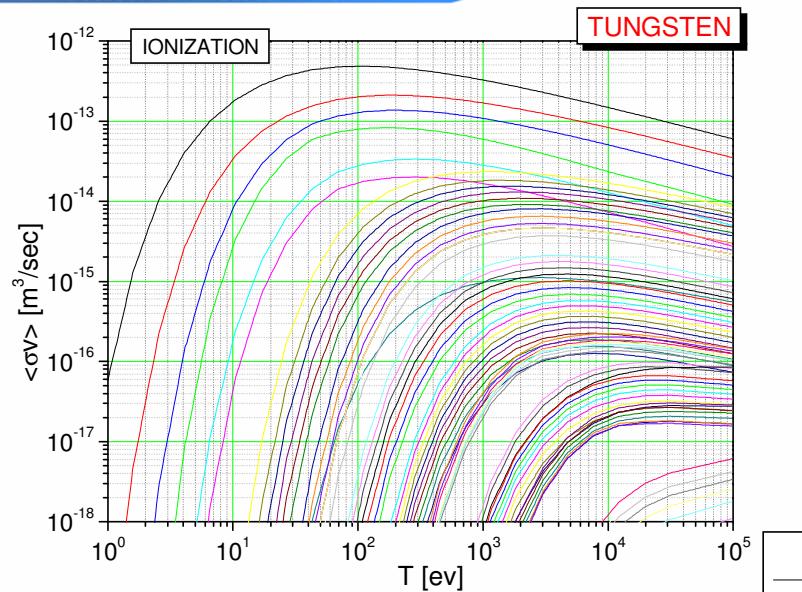
Thank you for your attention



EFDA

EUROPEAN FUSION DEVELOPMENT AGREEMENT





Cooling Rates for TUNGSTEN

